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Hydrology of Tidal Waters at the Glacier Terminus and their Impact on Hydrographical Surveys and Navigation Safety

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ABSTRACT: The data analysed in the paper are related to the hydrology of tidal waters at a tidewater glacier terminus. Set of data was collected in the wide span of time from 2009 till 2015 in the Nordaustlandet and Southwest Spitsbergen near various tidal glaciers terminus. The data are related to tidal phenomenon, calving glacier, drifting ice, hydrology of brackish water from ice of glacial origin and theirs consequences on safety of navi-gation. Thus, results of analysis of hydrological data may serve for improvement of safety of maritime transport in polar regions on high latitudes in vicinity of tidewater glaciers.
The research work was part of the reconnaissance of hydrological and hydrographic conditions for the needs of other studies. Measurements were taken at the Kamavika inlet leading from the Hans Glacier to-wards Hornsund fjord (Southern Svalbard). Based on above data, the causes of disturbances and errors of hydrographic measurements that may occur in area of occurrence of brackish water layer and their influence on errors of digital information displayed in ECDIS systems as well as prediction of ice conditions and safety of watercrafts in vicinity of glacier terminus and on anchorage were described.

1 INTRODUCTION

During the research conducted in the years 2009-2010 in the Nordaustlandet and Southern Svalbard regions by means of a multi-beam echosounder on board vessel "Horyzont II" (Moskalik et al. 2012, Pastusiak 2011, 2012, Pohjola et al. 2011), the occurrence of interference of the recorded signals of a multi-beam echosounder was noticed. This happened mostly in front of the mouth of the main water outflow from individual glaciers to the sea. This disturbance consisted in incorrect indication of spatial distribution of the depth along the single and subsequent beams of the multi-beam echosounder. Sometimes a series of subsequent pings had a random distribution or the bottom image disappeared completely.

Purpose of the research was detection of the causes of disturbances, determining the extent of the phenomenon, determining the impact of the phenomenon on safety of navigation and finally proposing preventive measures. In order to discover the causes of the phenomenon, it was decided to carry out hydrological and hydrographic measurements near the terminus of the Hans Glacier (Hansbreen). The glacier is located in the southern part of Spitsbergen in the Hornsund fjord 77° 00′ N (Fig.1) and has a very high calving intensity. The calving intensity of the Hans Glacier is much higher than for other glaciers in the Hornsund fjord. The Hans Glacier is located closest to the mouth of the Hornsund fjord into the Atlantic Ocean. The southwest coast of Spitsbergen is surrounded by the warm waters of the West-Spitsbergen Current (Arntsen et al. 2019, Promińska et al. 2018). Hence, it was expected that the most intense impact of warm waters of the West-Spitsbergen Current occurs at the mouth of the fjord into the ocean. So, it should allow better identification of the phenomenon.

2 PRELIMINARY ASSUMPTIONS AND RESEARCH METHOD

It was decided to take measurements of water salinity and temperature in the horizontal plane (on the sea surface) during high and low water. The hydrology study was supplemented by a few temperature and salinity profiles along the axis of the Kamavika inlet and the recording of a single-beam echosounder image with individual pings. It was expected that the sonar and individual ping image recording would indicate the causes and location of the sonar signal interference.

Important from the point of view of the research objective was the proper selection of points and measurement lines. Initial observations of the surveyed region showed four characteristic boundaries of the examined region located transversely to the axis of the inlet at Hans Glacier terminus (Kamavika). The first was the external border of the inlet, at which the shoreline changed its direction by nearly 90 ° (Fig. 1). The second characteristic place slightly distant from the shoreline was the outer end of the glacier on land. Five measuring points were determined on the line connecting these ends of the Hans Glacier. The total length of the measuring line was 1.415 meters. The third characteristic place was the end of the beach (shoreline) at the glacier wall when high water occurred. The next five measurement points were determined on the line connecting the ends of the beach. The total length of the measuring line was 1.453 meters. The fourth characteristic place was the border of the glacier terminus, which was reached by the beach uncovered during low water. There is no measuring point between the inner line (4th reference line) and the glacier terminus due to intense calving and retention of concentrated ice debris with individual dimensions up to 30 meters long and up to 4 meters high above the water surface.

Additionally, 6 measuring points were determined along the axis (central line) of the Hans Glacier inlet from the line connecting the outer borders of the inlet (1st reference line) to the inner line of the glacier (4th reference line). The total length of the measuring line was 1.462 meters. The nearest measuring point was located about 300 meters in front of the glacier terminus. Each of these lines had one point in common with the center line. The length of Kamavika inlet from the glacier terminus (4th transverse line) to the mouth of the inlet to the Hornsund fjord (1st transverse line) measured along its axis was 2.040 meters.

Three measuring points for the CTD probe were determined on the axis of the Hans Glacier inlet. They were determined at the outer point of the axis (reference point No. 13) and one at each intersection of the axis with reference transverse lines (reference points No. 3 and 8). The measured depth at the outer point (No. 13) was limited by the depth of the basin and at the other two points (No. 3 and 8) was limited by the length of the CTD probe line.

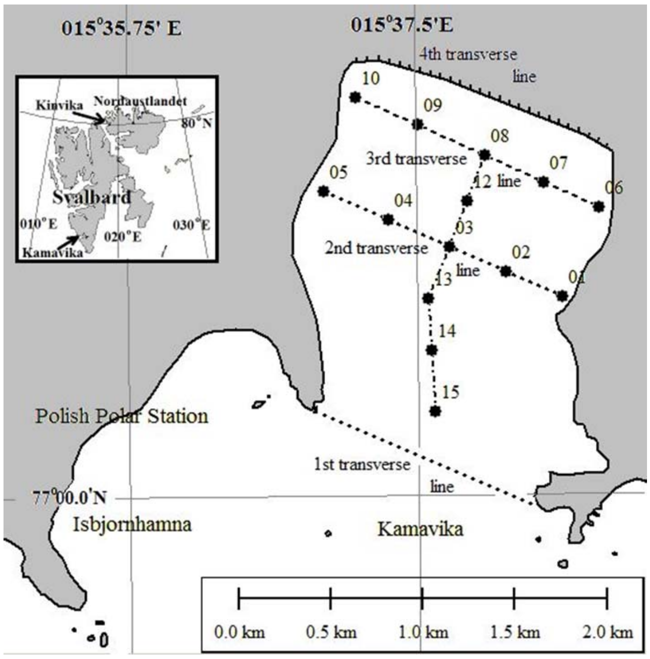

Figure 1. Distribution of measuring points on depth profiles: · · · · - external glacier transverse line, - - - - internal glacier transverse line, · - · - post-glacial valley axis; ——— - shoreline, LLL - the Hans Glacier terminus, the base of which is always immersed. Compiled by author.

The periods of high and low water available for measurement purposes were determined on the basis of calculating the British Admiralty tide table (UKHO 2015) for the port connected to "Isbjornhamna" and time restrictions related to hydrological and meteorological conditions occurring in the research area, time restrictions resulting from other measurements and the duration of the stay of persons performing measurements and availability of assistants in the region of Isbjornhamna. The prevailing ice conditions in the inlet at the Hans Glacier terminus were not a criterion for making decisions about the timing of measurements. Due to the above time limitations, hydrological measurements during the low water period were made before the lowest water level and during the high water period were made after the highest water time.

3 RESULTS OF MEASUREMENTS

Salinity and water temperature profiles were compiled at three reference points located along the axis of the Kamavika inlet at Low Water time. The salinity change graph (Fig. 2) shows a significant increase in the salinity gradient with increasing depth at all three reference points from the sea surface to a depth of 1.1 meter. Similarly, a significant increase in the sea water temperature gradient occurs at all three reference points from the sea surface to a depth of 2.0 meters (Fig. 3). In both diagrams (Fig. 2 and Fig. 3) are very small changes of water salinity and temperature from 20 meters depth and deeper. Slight increase of water temperature and salinity is noted for external reference point 13. Changes of water temperature were much more instable than changes of water salinity.

Then, average salinity and water temperature values for all vertical profiles (Fig. 2 and Fig. 3) made by the author in 2015 and average results for measurements made in 2015 by Prominska et al. (2017) were compared. Profiles made by Prominska et al. (2017) concerned general direction along the Hornsund fjord axis and across the fjord but far away from any glacier terminus. Profiles made by the author related to deep inside glacier inlet and very close to glacier terminus. Average temperature at glacier terminus inside glacier inlet in 2015 was +1.80°C (by the author) and average temperature at the axis of Hornsund fjord and far away from any glacier terminus (Prominska et al. 2017) was +2.27°C. Average salinity at glacier terminus inside glacier inlet in 2015 was 31.57 (by the author) and average salinity at the axis of Hornsund fjord and far away from any glacier terminus (Prominska et al. 2017) was 34.6. Comparison of these data indicates higher influence of cold and fresh water from calving glacier on average parameters of brackish water in glacier inlet (at glacier terminus) than at centerline of the fjord far away from any glacier terminus.

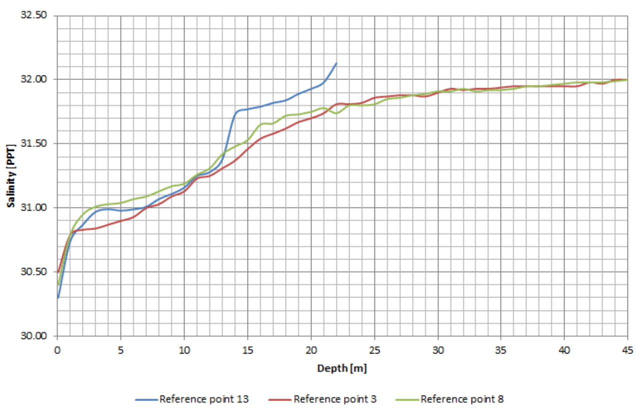

Figure 2. Changes in water salinity with depth for selected reference points in the axis of the Kamavika inlet at Low Water near the terminus of the Hans Glacier (Hansbreen) on 20.09.2015. Compiled by author.

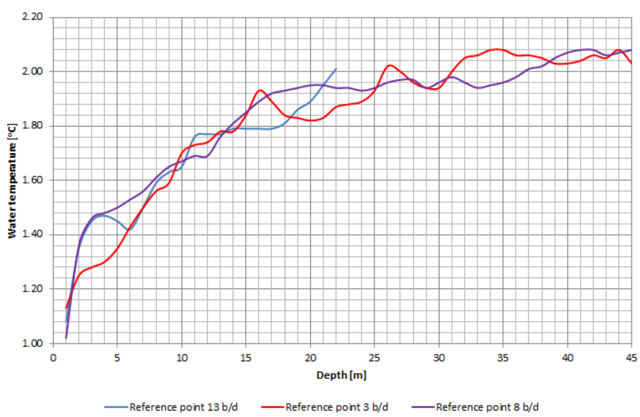

Figure 3. Changes in water temperature with depth for selected reference points in the axis of the Kamavika inlet at Low Water near the terminus of the Hans Glacier (Hansbreen) on 20.09.2015. Compiled by author.

The height of the brackish water layer (Tables 1 and 2) depended on the occurrence of a water zone covered with ice from the calving glacier in the vicinity of a given reference point (Fig. 4). On the depth charts recorded by a single-beam echosounder on longitudinal and transverse profiles to the axis of the Kamavika inlet, it was observed that the smallest heights of the layer of brackish water occurred near the inlet coastline (small depths of the basin) and the largest along the inlet centerline (large depths of the basin).

The direction and speed of tidal stream at the beginning and end of ebb tide were very convergent. The average direction of ebb stream was 206 °. The average speed of ebb stream was 0.16 m/s. The median ebb stream movement coincided with the mean values and was 195 ° and 0.13 m/s, respectively. These results are consistent with the work of Arntsen et al. (2019), where average speed of ebb stream along the largest depths over sill of Brepollen in 2013 was 0.02 m/s in the period 2010/2011 (0.01 m/s in the period 2013/2014. Same time maximal ebb stream speed (Arntsen et al. 2019), was 0.27 m/s in 2010/2011 and 0.37 m/s in 2013/2014.

If the movement of water in accordance with the median speed is assumed, then the ice which has calved from the glacier at the moment of High Water (4th transverse line) and fresh water of glacial origin will be outside the Kamavika inlet (1st transverse line) after 4 hours and 20 minutes. In case ice debris moves with same speed after passing entrance to the Kamavika inlet towards open sea, it reaches coastline at Polish Polar Station in Hornsund fjord after next 3 hours. In practice, there are strong winds towards open sea (Atlantic Ocean) and drift of ice is relatively much faster. It means ice calved from Hans Glacier terminus at High Water time is able to reach Polish Polar Station coastline during 5-7 hours. This is important conclusion for prediction of ice conditions at the coastline for anchoring, cargo operations, supplies and people transfer from vessel to Polish Polar Station and vice versa. Prediction of ice conditions during planned transfer operations should be based on quantity (low or high) of debris from calved Hans Glacier at High Water time and quantity of debris pressed by the wind to the western coast of Kamavika inlet.

Ice debris originated from calving glacier is maximally compacted from 1-2 hours before High Water till 1-2 hours after High Water (Pastusiak 2018, 2020). It was experienced during surveys at Hans Glacier terminus in 2015, that the assessment of amount of compacted ice debris from calving glacier during High Water time at glacier terminus allows prediction of amount of drifting ice which will reach coastline at the Polish Polar Station in Hornsund fjord at the same time. It should be mentioned that a large amount of drifting compacted ice can prevent trans-shipment operations at coastline. Thus, it will be possible to determine conditions for staying of vessel at anchorage and conditions for carrying out trans-shipment operations at the side of the vessel and at coastline.

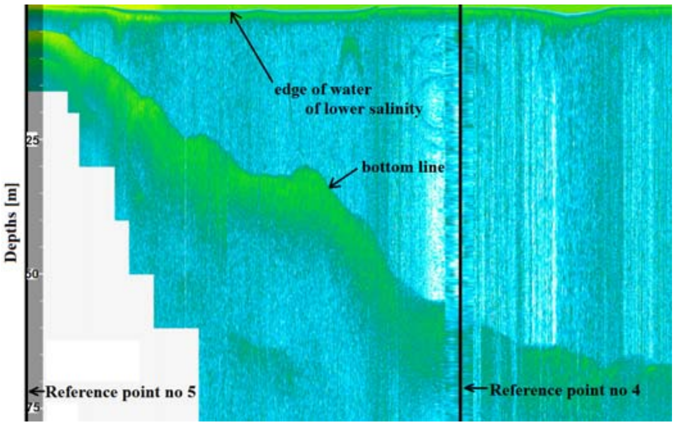

Figure 4. The height of the water layer and the depth of the basin on the profile registered with a single beam echosounder. Compiled by author.

From the above results it was stated that any watercraft (research vessel, yacht, boat, pontoon) should not approach the coastline of unsurveyed or poorly surveyed bathymetry where exists drifting ice debris from calving glacier 3 hours before High Water at glacier terminus. The increasing concentration of ice and compactness of ice in the period from 1-2 hours before High Water till 1-2 hours after High Water at glacier terminus can beset and nip a watercraft in such ice. The event is dangerous because an immobilized watercraft can drift along with the surrounding ice debris and be dragged to rocky shoals, suffer damage of hull or machinery or even sink (Pastusiak 2018, 2020). A vessel that is beset or nip in compacted ice in vicinity of glacier terminus may suffer damage, collapse or even sink as a result of calved piece of glacier or high waves or surges.

Table 1. Hydrological and surface water movement parameters at reference points determined during Low Water in Kamavika inlet near the terminus of the Hansbreen Glacier on 20.09.2015. Compiled by author.

Reference point	Speed of tidal stream [m/s]	Direction of tidal stream [°]	Salinity of surface water layer [PSU]	Height of brackish water layer H_{aver} [m]
1	0.1	195	30.4	0.3
2	0.3	189	30.1	0.3
3	0.05	211	30.5	0.5
4	0.05	135	29.9	1
5	0.1	283	29.6	0.9
6	0.15	307	30.3	0.6
7	0.1	270	30.3	1.3
8	0.25	180	30.4	0.7
9	0.15	226	30.4	1
10	0.1	110	30.9	1
12	0.15	258	30.4	0.4
13	0.2	133	30.3	0.9
14	0.15	189	30.4	0.8
15	0.1	193	28.5	0.8
Average	0.1	214.9	30.2	0.7

Table 2. Hydrological and surface water movement parameters at reference points determined during High Water in Kamavika inlet near the terminus of the Hansbreen Glacier on 25.09.2015. Compiled by author.

Reference point	Speed of tidal stream [m/s]	Direction of tidal stream [°]	Salinity of surface water layer [PSU]	Height of brackish water layer H_{aver} [m]
1	0.24	180	29.9	0.5
2	No data	b/d	28.8	0.7
3	0.11	180	28.9	1.3
4	No data	No data	28.7	0.5
5	0.06	181	23.3	0.3
6	0.13	240	29.9	0.9
7	No data	No data	29.4	0.7
8	0.6	250	30.4	1.3
9	0.05	224	28.0	0.4
10	0.26	223	25.8	0.6
12	0.15	197	29.1	1.4
13	No data	No data	29.4	b/d
14	No data	No data	29.2	b/d
15	No data	No data	29.1	No data
Average	0.2	209.4	28.6	0.8

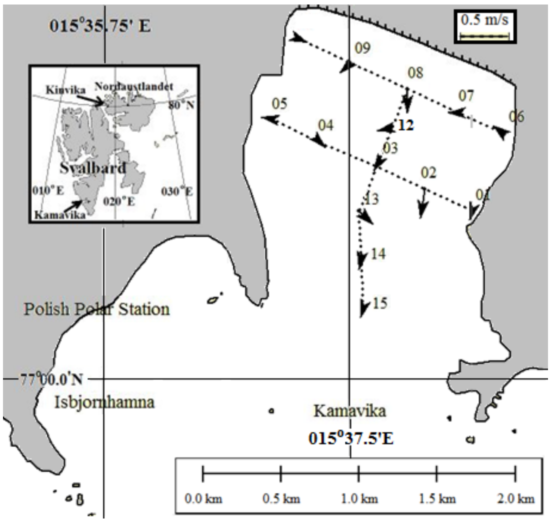

Figure 5. Direction and speed of surface tidal stream determined at Low Water in Kamavika inlet near the terminus of the Hansbreen Glacier on 20.09.2015. Compiled by author.

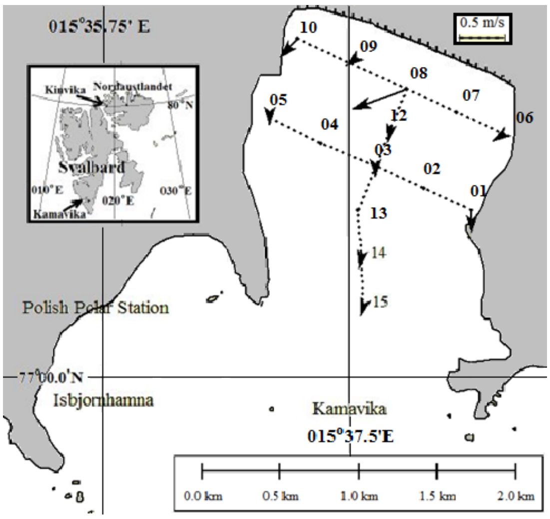

Figure 6. Direction and speed of surface tidal stream determined at High Water in Kamavika inlet near the terminus of the Hansbreen Glacier on 25.09.2015. Compiled by author.

The direction of the tidal stream (Figures 5 and 6) at the beginning and end of the ebb tide (outflow) was predominantly parallel to the longitudinal centerline of the Kamavika inlet along its entire length with a tendency to diverge towards greater depths that lead mostly at a centerline of the Kamavika inlet (Jania et al. 2016). This is consistent with the results of Arntsen et al. (2019), where general direction of flood stream and ebb stream was found consistent with the direction along the largest depths over sill of Brepollen.

4 THE REASONS OF DISTURBANCES AND ERRORS OF HYDROGRAPHIC MEASUREMENTS

First, depth measurement was performed, a traditional image of the echosounder and georeferenced depths (pings) were automatically recorded on a cross section perpendicular to the axis of the Kamavika inlet near the 1st transversal line (Fig. 1). When performing measurements on pontoon, a single-beam echosounder worked on frequency 200 kHz. The closer it was to the mouth of Kamavika inlet, the more depth errors the sonar showed (electronic digital depth indicator). Recorded pings showed ever smaller depths until depth reached a value less than one meter at the axis of the cove (Fig. 7). Then the echosounder stopped visualizing the detected depths and has reset itself (Fig. 7). After restarting the echosounder, the dialog box reported necessity of performing the test due to the echosounder system failure. Echosounder software could not automatically eliminate misinterpretation of echoes returning from the depths of the water. This echosounder started to function properly only after the pontoon left the drifting ice field from the calving glacier and its surrounding water. Further measurements of the longitudinal and transverse profiles in Kamavika inlet were made at an operating frequency of 83 kHz. So, when pontoon was moving along the same test route, the echosounder worked incorrectly at 200 kHz and correctly at 83 kHz. At a lower frequency, the echosounder showed received echoes from the water depth correctly and recorded georeferenced depths (pings) correctly. Further measurements of longitudinal and transverse profiles in the Kamavika inlet were made on 83 kHz working frequency. No interference was found.

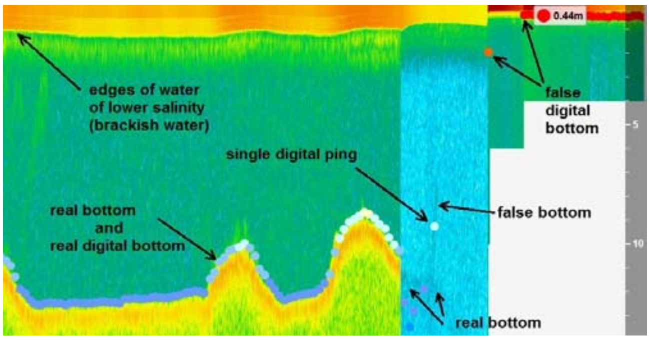

Figure 7. Depth discrepancy indications of automatically recorded georeferenced individual depths (pings) relative to the recorded echo image on the echosounder screen. Compiled by author.

Next, were analyzed the depth measurements, which were made using a multi-beam echosounder on board vessel "Horyzont II" on 22.09.2015. Transducers of this multi-beam echosounder worked at 180 kHz. When vessel was navigating deep into the Hornsund fjord, the multi-beam echosounder showed already incorrect depths on the traverse of Kamavika inlet (Fig. 8). In the central part of the mouth of the inlet echosounder suffered significant interference and incomplete measuring beams.

The results of multi-beam echosounder measurements in the vicinity of glaciers terminus in the Brepollen area (in 2010), right at the glaciers terminus, when reached glaciers walls, also showed distortions of the beam shape (transverse profile) in some places. The phenomenon occurred near glaciers only. It can be explained that the disturbance of the bottom line shape (beam) resulted from the research vessel's entry into the water outflow zone of glacial origin. This brackish water was of high variability in temperature and salinity same like found at Kamavika inlet (Figures 2 and 3).

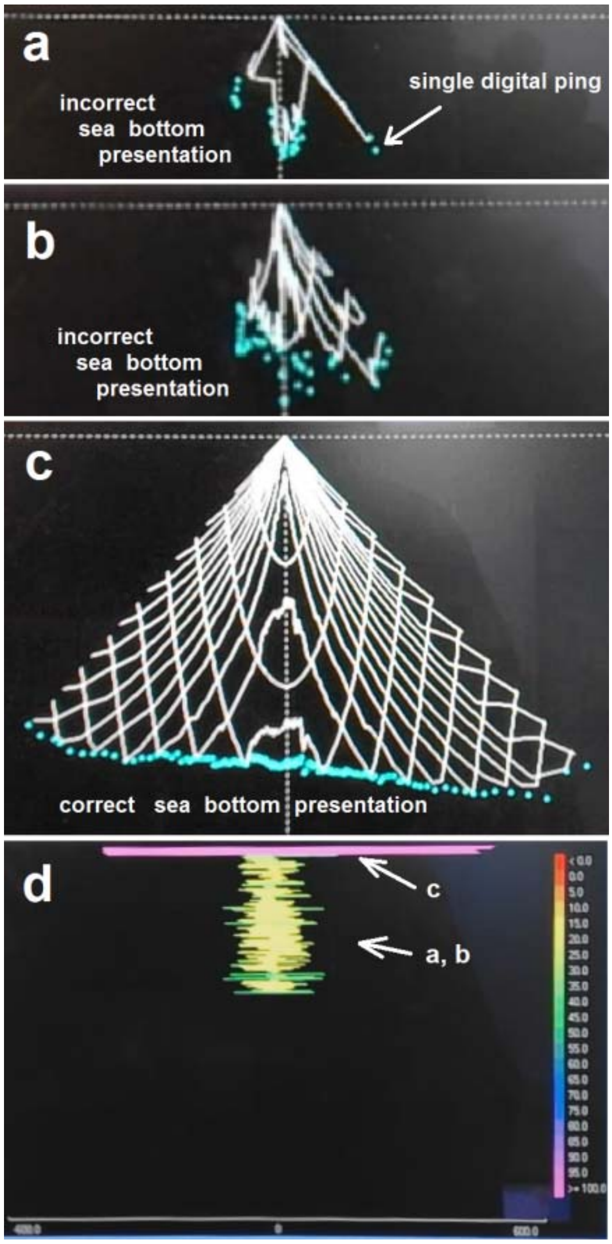

Figure 8. Multi-beam echosounder profiles along the front of Kamavika inlet in the middle of the ebb tide on 22.09.2015. Compiled by author.

Most probable reason of incorrect soundings were measurements of multi-beam echosounder, which were closest to glaciers. They presented incorrect shape of sea bottom in some places. Assumed these incorrect measurements of shape of seabed happened when vessel entered zone of water flowing out of the glacier. This brackish water was of variable temperature and salinity.

Depth measurements made with a multi-beam echosounder in subsequent stages when passing along mouth of the Kamavika inlet are presented Figure 8. The multi-beam echosounder worked at 180 kHz. While moving vessel along the mouth of the inlet, the echosounder indicated first incorrect depths (Figure 8a, d). Then, in the inlet axis, echosounder indicated incorrect sea bottom shape (Figure 8b, d). After passing the inlet, multi-beam echosounder presented shape of sea bottom correctly (Figure 8c, d).

Based on the two observed phenomena of incorrect indication of digital depths of two devices operating at a similar frequency of transducers, the geographical distribution of this phenomenon was determined (Fig. 9).

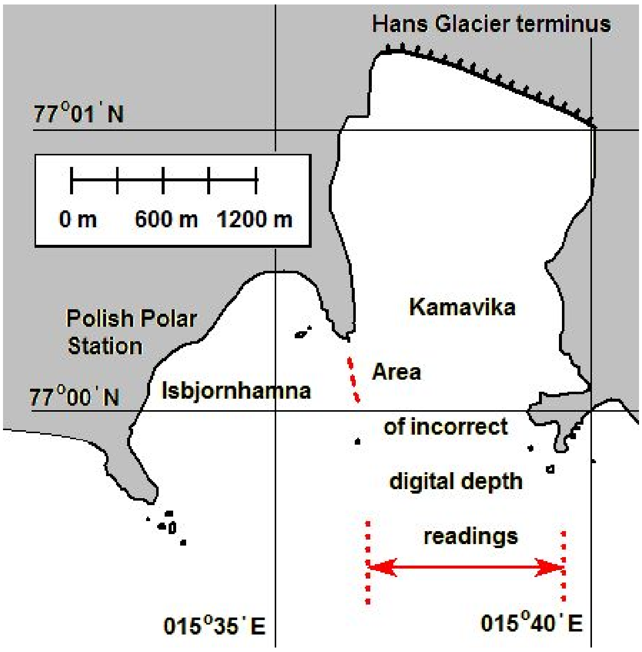

Figure 9. Identified area of incorrect digital readings of echosounders during ebb tide at Hans Glacier inlet; - - - edge of incorrect digital data on 20.09.2015 during survey on single-beam echosounder at 200 kHz, · · · area of incorrect digital data on 22.09.2015 during survey on multi-beam echosounder at 180 kHz. Compiled by author.

5 CONCLUSIONS

The data analysed in this paper are related to the hydrology of tidal waters at a glacier terminus. Set of data was collected in the wide span of time from 2009 till 2015 in the Nordaustlandet and Southwest Spitsbergen near various tidal glaciers terminus. The data are related to tidal phenomenon and its consequences on safety of navigation. Thus, results of analysis of hydrological data may serve for improvement of safety of maritime transport in polar regions on high latitudes.

The direction and speed of tidal stream at the beginning and end of ebb tide were very convergent. Average direction of ebb tide stream was set along the maximal depths or slight towards maximal depths of the basin. The average speed of ebb tide stream at the Hornsund fjord was about 0.01 m/s. Same time average speed at the beginning and end of ebb tide at the glacier terminus Kamavika inlet was 0.16 m/s and maximal speed at the Hornsund fjord was about 0.37 m/s.

The ice which has calved from the Hand Glacier at the moment of High Water and fresh water of glacial origin which is moving with the median ebb tide speed will be outside the Kamavika inlet after 4 hours and 20 minutes and there, under additional influence of the wind blowing towards open sea, may reach coastline at Polish Polar Station in Hornsund fjord after next 3 hours. Taking into consideration the variation of the wind speed the ice calved from Hans Glacier terminus at High Water time is able to reach Polish Polar Station coastline in 5-7 hours. This allows prediction of ice conditions at the coastline at Polish Polar Station for water craft anchoring as well as for equipment, supplies and people transfer. Prediction of ice conditions should be based on quantity of debris from calved Hans Glacier at High Water time and quantity of debris pressed by the wind to the western coast of Kamavika inlet. Thus, it is possible to determine conditions for staying of vessel at anchorage and conditions for carrying out trans-shipment operations at the side of a vessel and at shoreline.

Any watercraft (research vessel, yacht, boat, pontoon) should not approach the coastline of unsurveyed or poorly surveyed bathymetry where exists drifting ice debris from calving glacier 3 hours before High Water at glacier terminus. The increasing concentration of ice and compactness of ice in the period from 1-2 hours before High Water till 1-2 hours after High Water at glacier terminus can beset and nip a watercraft in such ice. This is dangerous because an immobilized watercraft can drift along with the surrounding ice debris and be dragged to rocky shoals, suffer damage of hull, machinery or scientific equipment or even sink. A watercraft that is beset or nip in compacted ice in vicinity of glacier terminus may suffer damage, collapse or even sink as a result of contact with calved piece of glacier or due to action of high waves or surges.

The direction of the tidal stream at the beginning and end of the ebb tide (outflow) is predominantly parallel to the longitudinal centerline of the glacier inlet along entire sea bed length with a tendency to diverge towards greater depths that are located mostly at a centerline of the inlet.

The speed of the ebb current allowed ice to drift from the calving glacier along with the surrounding brackish water to at least the border of the area of incorrect digital depth readings visible in the mouth of the glacier inlet. Incorrect, misleading depth readings of echosounder that is operating at frequency of 200 kHz and same time correct depth readings of echosounder operating at frequency of 83 kHz - can be used for detection of outflow of water from the glacier and demonstrate 3D range of the phenomenon. Incorrect indications of single-beam navigational echosounder may refer to the edge of water layers with different salinity or temperature and indicate smaller depths than they actually are (dangerous for navigation - may mislead the navigator, in case depth serve for vessel position verification). Incorrect single-beam echosounder digital indication may refer to the second or third echo (dangerous for navigation - indicates greater depths then they are).

The navigator (Officer On Watch) should often compare the depth digital indications on the ECDIS screen with the image on echosounder screen to detect incorrect indications. Manual change of settings of single-beam echosounder enables elimination of incorrect depth indications. The navigator (Officer On Watch) should be vigilant and recognize incorrect image of sea bottom shape of multi-beam echosounder pings. Tis case explain importance of human factor in safety of maritime transport.

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